

APPARATUS FOR REDUCING POWER SUPPLY NOISE  
IN AN INTEGRATED CIRCUIT

Cross-Reference To Related Applications

**[0001]** This application is a continuation-in-part of U.S. application serial no. 10/003,596, filed October 30, 2001, which is a divisional of U.S. application serial no. 09/484,600, filed January 18, 2000, now U.S. Patent No. 6,339,338 B1.

Background of the Invention

Field of the Invention

**[0002]** The present invention relates in general to systems for testing integrated circuits and in particular to an apparatus for reducing power supply noise in an integrated circuit under test resulting from state transitions of the logic it implements.

Description of Related Art

**[0003]** An integrated circuit (IC) tester can concurrently test a set of ICs in the form of die on a silicon wafer. FIG. 1 is a block diagram illustrating a typical IC tester 10 connected through a probe card 12 to a set of similar IC devices under test (DUTs) 14. Tester 10 uses pogo pins 15 or other means to connect various input and output terminals to a set of contacts 16 on probe card 12. Probe card 12 includes a set of probes 18 for contacting input/output (I/O) pads 19 on the surface of each DUT 14 and provides conductive paths 20 linking contacts 16 to probes 18. The paths through probe card 12 allow tester 10 to transmit test signals to DUT 14 and to monitor output signals produced by the DUT. Digital integrated circuits often include synchronous logic gates clocked in response to pulses of a periodic master clock signal (CLOCK). Therefore probe card 12 also provides a path 22 through which tester 10 may supply a CLOCK signal to each DUT 14. The test system also includes a power supply 24 for supplying power to DUTs 14 as they are being tested. Probe card 12 connects power supply 24 to a power input pad 26 of each DUT 14 through probes 18.

**[0004]** Each switching transistor within a DUT 14 has an inherent input capacitance, and in order to turn on or off the transistor, the transistor's driver must either charge or discharge the transistor's input capacitance. When a driver charges a transistor's input capacitance it draws charging current from power supply 24. Once the transistor's input capacitance is fully charged, its driver need only supply a relatively small amount of leakage current needed to keep the transistor's input capacitance charged so that the transistor remains turned on or off. In DUTs implementing synchronous logic, most transistor switching occurs immediately after an edge of each CLOCK signal pulse. Thus immediately after each pulse of the CLOCK signal, there is a temporary increase in the power supply current I1 input to each DUT 14 to provide the charging current necessary to change the switching states of various transistors within the DUT. Later in the CLOCK signal cycle, after those transistors have changed state, the demand for power supply current I1 falls to a "quiescent" steady state level and remains there until the beginning of the next CLOCK signal cycle.

**[0005]** The signal paths 28 through which probe card 12 connects power supply 24 to each DUT 14 have an inherent impedance represented in FIG. 1 by a resistance R1. Since there is a voltage drop between the output of power supply 24 and the power input 26 of DUT 14, the supply voltage input VB to DUT 14 is somewhat less than the output voltage VA of power supply 24, and although VA may be well-regulated, VB varies with the magnitude of current I1. After the start of each CLOCK signal cycle, the temporary increase in I1 needed to charge switching transistor input capacitance increases the voltage drop across R1, thereby temporarily reducing VB. Since the dip in supply voltage VB occurring after each CLOCK signal pulse edge is a form of noise that can adversely affect the performance of DUTs 14, it is desirable to limit its magnitude and duration. We can limit that noise by reducing the reactance of the paths 28 between power supply 24 and DUTs 14, for example by increasing conductor size or by minimizing the length of path 28. However there are practical limits to the amount by which we can reduce that reactance.

**[0006]** We can also reduce power supply noise by placing a capacitor C1 on probe card 12 near the power supply input 26 of each DUT 14. FIG. 2 illustrates the behavior of supply voltage VB and current I1 at the power input 26 of IC 14 in response to a pulse of the CLOCK signal input to IC 14 when capacitor C1 is

insufficiently large. Note that the temporary rise in  $I_1$  above its quiescent level  $I_Q$  following an edge of the CLOCK signal at time  $T_1$  produces a temporary increase in voltage drop across  $R_1$  that in turn produces a temporary dip in supply voltage  $V_C$  below its quiescent level  $V_Q$ .

**[0007]** FIG. 3 illustrates the behavior of  $V_B$  and  $I_1$  when capacitor  $C_1$  is sufficiently large. Between CLOCK signal pulses, when DUT 14 is quiescent, capacitor  $C_1$  charges to the quiescent level  $V_Q$  of  $V_B$ . Following a rising (or falling) edge of the CLOCK signal at time  $T_1$ , when a DUT 14 temporarily demands more current, capacitor  $C_1$  supplies some its stored charge to DUT 14 thereby reducing the amount of additional current power supply 24 must provide to meet the increased demand. As may be seen in FIG. 3, the presence of  $C_1$  reduces the magnitude of the temporary voltage drop across  $R_1$  and therefore reduces the magnitude of the dip in the supply voltage  $V_B$  input to the DUT 14.

**[0008]** For capacitor  $C_1$  to adequately limit variation in  $V_B$ , the capacitor must be large enough to supply the needed charge to DUT 14 and must be positioned close to DUT 14 so that the path impedance between  $C_1$  and DUT 14 is very low. Unfortunately it is not always convenient or possible to mount a large capacitor on a probe card 12 near the power supply input terminal 26 of each DUT 14. FIG. 4 is a simplified plan view of a typical probe card 12. IC tester 10 resides above the probe card and the wafer containing DUTs 14 is held below the probe card. Since the I/O terminals of IC tester 10 of FIG. 1 are distributed over a relatively large area compared to the surface area of the wafer being tested, probe card 12 provides a relatively large upper surface 25 for holding the contacts 16 the tester accesses. On the other hand, the probes 18 (not shown) on the underside of probe card 12 that contact DUTs 14 on the wafer are concentrated under a relatively small central area 27 of probe card 12.

**[0009]** The path impedance between contacts 16 on the upper surface 25 of card 12 and the probes 18 under area 27 is a function of the distance between each contact 16 and its corresponding probe. To minimize the distance between capacitors  $C_1$  and the DUTs, the capacitors should be mounted on probe card 12 near (or above) the small central area 27. However when a wafer includes a large number of ICs to be tested or an IC having a large number of densely packed

terminals, there is not enough space to mount the required number of capacitors C1 of sufficient size sufficiently close to central area 27.

### Summary of the Invention

**[0010]** During a test of an integrated circuit device under test (DUT) employing synchronous logic, the DUT experiences a temporarily increase in its demand for power supply current after each pulse of a clock signal input to the DUT because each clock signal pulse initiates state transitions of clocked logic devices within the DUT. The DUT needs the extra current to charge input capacitance of transistors forming those logic devices. It is an object of the invention to provide a means for limiting variation in power supply voltage at the power input terminal of a DUT arising from the transient increase in power supply current following each clock signal pulse, thus reducing the power supply noise at the DUT.

**[0011]** In accordance with one aspect of the invention, a charging current is supplied to the DUT's power input terminal from an auxiliary power supply source after each clock signal pulse to supplement a current continuously supplied by a main power supply during the test. The additional charging current reduces the need for the main power supply to increase its output current to meet the DUT's increased demand. With the output current of the main power supply being held substantially constant despite the DUT's increased demand for current, any voltage drop across path impedance between the main power supply and the DUT remains substantially constant. Thus the supply voltage at the DUT's power input terminal remains substantially constant.

**[0012]** The amount of additional charging current a DUT requires after each clock signal pulse varies depending on the state transition its internal logic devices undergoes in response to the clock signal pulse. In accordance with another aspect of the invention the additional charging current supplied is adjusted to match a predicted value of transient charging current required by the DUT following each clock signal pulse.

**[0013]** In accordance with a further aspect of the invention, in a preferred embodiment thereof, the auxiliary power source includes a capacitor, a transistor switch and a voltage source. The voltage source charges the capacitor before each clock signal pulse and the switch temporarily connects the capacitor to the

DUT's power input terminal at the start of each clock cycle so that the capacitor can deliver its charge to the DUT to provide the DUT's required transient charging current. The voltage to which the capacitor is charged is adjusted prior to the start of each clock signal cycle so that the capacitor delivers the amount of charge the DUT is predicted to require during the next state change. The system can regulate the DUT's supply voltage even when there is significant path impedance between the capacitor and the DUT. Thus the capacitor may be mounted on a probe card relatively distant from DUT.

**[0014]** In accordance with a further aspect of the invention, in an alternative embodiment thereof, a DUT and a reference IC similar to the DUT are tested at the same time. However the reference IC is tested slightly in advance of the DUT so that variations in the input power supply voltage of the reference IC due to changes in its current demand predict subsequent similar variations in the input current demand of the DUT. An amplifier amplifies variations in the voltage at the power input terminal of the reference IC to produce the time-varying charging current needed by the DUT. The lag between the tests performed on the reference DUT and the second DUT is adjusted to match a signal path delay through the amplifier and interconnect path.

**[0015]** In accordance with yet a further aspect of the invention, a supplemental current is supplied to the power input terminal. The amount of the supplemental current is related to an amount of additional current temporarily drawn by the power input terminal.

**[0016]** The concluding portion of this specification particularly points out and distinctly claims the subject matter of the present invention. However those skilled in the art will best understand both the organization and method of operation of the invention, together with further advantages and objects thereof, by reading the remaining portions of the specification in view of the accompanying drawing(s) wherein like reference characters refer to like elements.

### Brief Description of the Drawing(s)

- [0017]** FIG. 1 is a block diagram illustrating a typical prior art test system including an integrated circuit tester connected through a probe card to a set of integrated circuit devices under test (DUTs),
- [0018]** FIGS. 2 and 3 are timing diagrams illustrating behavior of signals within the prior art test system of FIG. 1,
- [0019]** FIG. 4 is a simplified plan view of the prior art probe card of FIG. 1,
- [0020]** FIG. 5 is a block diagram illustrating a test system implementing a system for reducing noise in the power supply inputs of a set of DUTs in accordance with a first embodiment of the present invention;
- [0021]** FIG. 6 is a timing diagram illustrating behavior of signals within the test system of FIG. 5,
- [0022]** FIG. 7 is a block diagram illustrating operation of the test system of FIG. 5 during a calibration procedure;
- [0023]** FIG. 8 is a simplified plan view of the probe card of FIG. 6;
- [0024]** FIGS. 9 and 10 are block diagrams illustrating test systems implementing second and third embodiments of the present invention;
- [0025]** FIG. 11 is a timing diagram illustrating behavior of signals within the test system of FIG. 10;
- [0026]** FIGS. 12 is a block diagram illustrating a test system implementing a fourth embodiment of the present invention;
- [0027]** FIG. 13 is a timing diagram illustrating behavior of signals within the test system of FIG. 12;
- [0028]** FIG. 14 is a block diagram illustrating a fifth embodiment of the present invention;
- [0029]** FIG. 15 is a block diagram illustrating a sixth embodiment of the present invention;
- [0030]** FIG. 16 is a block diagram illustrating a seventh embodiment of the present invention; and
- [0031]** FIG. 17 is a timing diagram illustrating behavior of signals within the circuit of FIG. 16.
- [0032]** FIG. 18 is a block diagram illustrating an eighth embodiment of the invention.

**[0033]** FIG. 19 is a block diagram illustrating a ninth embodiment of the invention.

**[0034]** FIG. 20A illustrates an exemplary probe card.

**[0035]** FIG. 20B illustrates another exemplary probe card.

### Description of the Preferred Embodiment(s)

#### System Architecture

**[0036]** FIG. 5 illustrates in block diagram form an integrated circuit (IC) tester 30 linked through a probe card 32 to a set of similar IC devices under test (DUTs) 34 in the form of die on a semiconductor wafer. Probe card 32 includes a set of probes 37 for accessing input/output terminal pads 39 on the surfaces of DUTs 34 and also includes signal paths 46 linking tester 30 to probes 37 to allow IC tester 30 to send a clock signal (CLOCK) and other test signals to DUTs 34 and to convey DUT output signals back to tester 30 so that the tester can monitor the behavior of the DUTs.

**[0037]** Probe card 32 also links a main power supply to a power input terminal 41 of each DUT 34 via probes 37. Power supply 36 produces a well-regulated output voltage  $V_A$  and continuously supplies a current  $I_2$  to DUT 34. For illustrative purposes, FIG. 5 represents the inherent impedances of the paths 43 through probe card 32 between main power supply 36 and each DUT 34 as resistors  $R_1$ . Due to a voltage drop across resistor  $R_1$ , the input supply voltage  $V_B$  to each DUT 34 is always somewhat less than  $V_A$ .

**[0038]** In accordance with the invention, a first transistor switch  $SW_1$  mounted on probe card 32 links an auxiliary power supply 38 to a set of capacitors  $C_2$  mounted in probe card 32. A set of second transistor switches  $SW_2$  also mounted on probe card 32 link each capacitor  $C_2$  to the power input terminal of a corresponding DUT 34. A resistor  $R_2$  shown in FIG. 5 represents the inherent signal path impedance within probe card 32 between each capacitor  $C_1$  and the power input terminal 41 of a DUT 34 when switch  $SW_2$  is closed. IC tester 30 provides an output control signal  $CNT_1$  for  $SW_1$ , a control signal  $CNT_2$  for controlling switches  $SW_2$  and control data  $CNT_3$  for controlling the magnitude of the output voltage  $V_C$  of auxiliary power supply 38. As discussed in detail below, auxiliary power supply 38, switches  $SW_1$  and  $SW_2$  and capacitors  $C_2$  act as an

auxiliary current source to inject current  $I_3$  into the power input terminal 41 of each DUT under control of IC tester 30.

### Power Supply Noise

**[0039]** DUTs 34 implement synchronous logic in which switching transistors forming logic gates turn on and off in response to pulses of the periodic master CLOCK signal provided by tester 30. Each switching transistor has an inherent input capacitance, and in order to turn on or off the transistor, its driver must either charge or discharge the transistor's input capacitance. When drivers within DUTs 34 charge a transistor's input capacitance they increase the amount of current  $I_1$  that must be supplied to each DUT's power input terminal 41. Once the transistor's input capacitance is fully charged, its driver need only supply the relatively small amount of leakage current needed to keep the transistor's input capacitance charged so that the transistor remains turned on or off. Thus immediately after each pulse of the CLOCK signal, there is a temporary increase in the power supply current  $I_1$  input to each DUT 34 to provide the charging current necessary to change the switching states of various transistors. Later in a CLOCK signal cycle, after those transistors have changed state, the demand for power supply current falls to a "quiescent" steady state level and remains there until the beginning of the next CLOCK signal cycle. The amount of additional current  $I_1$  a DUT 34 needs at the start of each CLOCK signal cycle depends on the number and nature of transistors that turn on or off during that particular CLOCK signal cycle.

**[0040]** If tester 30 always kept switches SW1 and SW2 open, main power supply 36 would always provide all of the current input  $I_1$  to each DUT 34. In such case the temporary increase in supply current  $I_1$  due to the increased switching activity within each DUT 34 after each CLOCK signal pulse would cause a temporary increase in the voltage drop across the inherent impedance  $R_1$  of the signal path 43 between main power supply 36 and DUT 34. This in turn would cause a temporary decline in the voltage  $V_B$  at the DUT's power input terminal 41. FIG. 2 represents the behavior of  $V_B$  and  $I_1$  when SW2 is always open. Since the dip in supply voltage  $V_B$  occurring after each CLOCK signal pulse edge is a form of noise that can adversely affect the performance of DUTs 34, it is desirable to limit the magnitude of that voltage dip.



## Predictive Charge Compensation

**[0041]** In accordance with the invention, IC tester 30 controls auxiliary power supply 38 and the states of switches SW1 and SW2 so that capacitor C2 supplies additional charging current I3 to DUT 34 at the start of each test cycle. The charging current I3, which only flows during an initial portion of each CLOCK signal cycle, combines with the current I2 output of the main power supply to provide the current input I1 to DUT 34. When charging current I3 provides approximately the same amount of charge the capacitance of switching transistors within DUT 34 acquire following a CLOCK signal pulse, there is relatively little change in the current I2 produced by main power supply 36 following the CLOCK signal pulse and therefore very little variation in supply voltage VB.

**[0042]** Thus prior to each CLOCK signal pulse, tester 30 supplies data CNT3 to auxiliary power supply 38 indicating a desired magnitude of VC and then closes switch SW1. Power supply 38 then charges all capacitors C2. The amount of charge capacitors C2 store is proportional to the magnitude of VC. When capacitors C2 have had time to fully charge, tester 30 opens switch SW1. Thereafter, at the start of the next CLOCK signal cycle, tester 30 closes all switches SW2 so that charge stored in capacitors C2 can flow as currents I3 into DUTs 34. Thereafter, when the need for transient charging current has passed, tester 30 opens switches SW2 so that only main power supply 36 supplies current to DUTs 34 during the remaining portion of the CLOCK signal cycle. This process repeats during every cycle of the CLOCK signal.

**[0043]** FIG. 6 illustrates the behavior of supply voltage VB, and currents I1, I2 and I3 during an initial portion of a CLOCK signal cycle. Current I1 exhibits a large temporarily increase above its quiescent level IQ1 after an edge of the CLOCK pulse at time T1 to charge capacitance within the DUT 34. Current I3 rises quickly to provide substantially all the additional charging current. The output current I2 of main power supply 38 exhibits only a relatively small perturbation from its quiescent value IQ2 resulting from small mismatches between I3 and the transient component of I2. Since the variation in I2 is small, the variation in VB is small. Thus the present invention substantially limits the power supply noise due to switching transients in DUTs 34.

## Tester Programming

**[0044]** As mentioned above, the amount of additional charging current each DUT 34 draws at the start of a CLOCK signal cycle depends on the number of transistors that turn on or off during the CLOCK signal cycle and charging current varies from cycle-to-cycle. In order to provide proper voltage regulation at DUT terminal 41, tester 30 has to predict how much charge DUT 34 is going to store following the each CLOCK signal pulse because it has to adjust the magnitude of auxiliary power supply output VC so that capacitors C2 store the proper amount of charge prior to each CLOCK signal cycle.

**[0045]** FIG. 7 depicts a test system set up that allows tester 30 to experimentally determine the level to which it should set VC for each test cycle. A reference DUT 40 that is known to operate properly and which is similar to the ICs to be tested, is connected to tester 30 via probe 32 in generally the same way DUTs 34 are to be connected so that tester 30 can perform the same test on reference IC 40. However probe card 32 also links the power supply terminal of reference IC 40 to an input terminal of tester 30 so that tester 30 can monitor the power supply voltage VB. Tester 30 then executes only the first CLOCK cycle of the test while observing VB using the minimum value for VC. If VB falls below a desired lower limit during the CLOCK signal cycle, tester 30 repeats the first CLOCK signal cycle of the test using a higher value of VC. This process is repeated iteratively until an appropriate value of VC for the first CLOCK signal cycle is established. The tester then iteratively executes the first two CLOCK signal cycles of the test while monitoring VB during the second CLOCK signal cycle and adjusting VC accordingly. The same procedure is used to establish an appropriate value of VC for each successive CLOCK signal cycle of the test. Those values for VC may then be used when testing DUTs 34.

**[0046]** Designers typically use circuit simulators to simulate ICs before they are fabricated. When a circuit simulator performs the same test on simulated ICs that an IC tester would perform on its real counterpart, the circuit simulator can be employed in an analogous manner to determine the sequence of VC values to be used during a test of the real IC.

## Probe Card

**[0047]** FIG. 4 illustrates a typical prior art probe card 12 that connects voltage regulating capacitors C1 to the power input terminals of DUTs to limit power supply noise. Such probe cards must minimize the distance between voltage regulating capacitors and the DUTs so as to minimize the impedance between the capacitors and the DUTs. Thus the capacitors preferably are mounted on the probe card in or near a small area 27 above the probes that access the DUTs. Since there is little space on the probe card near the probes, the size and number of regulating capacitors C1 that can be deployed on probe card 12 is limited. This limitation on capacitor mounting space can limit the number of DUTs that can be concurrently tested.

**[0048]** FIG. 8 is a simplified plan view of the probe card 32 of FIG. 5 in accordance with the invention. Contact points 45 accessed by IC tester 30 of FIG. 7 are distributed over a relatively large area of the upper surface 43 of probe card 32 while the probes 37 (not shown) that contact DUTs 34 are concentrated under a relatively small central area 47 of the probe card. Since the voltage VC to which capacitors C2 are charged can be adjusted to accommodate significant path impedance R2 (FIG. 5) between any switch SW2 and terminal 41 of DUT 34, capacitors C2 can be mounted on probe card 32 at a significantly greater distance from central area 47 above the DUT probes than capacitors C1 of FIG. 4. Also since capacitors C2 are charged to a higher voltage than capacitors C1, they can be smaller than capacitors C1. Since capacitors C2 of probe card 32 of FIG. 8 can be smaller and further from the center of the probe card than capacitors C1 of the prior art probe card 12 of FIG. 4, a larger number of capacitors C2 can be mounted on probe card 32. Thus a test system employing probe card 32 in accordance with the invention can concurrently test more DUTs than a test system employing a prior art probe card 12 of FIG. 4.

#### Probe Card With On-Board Pattern Generator

**[0049]** FIG. 9 illustrates an alternative embodiment of the invention including a probe card 50 generally similar to probe card 32 of FIG. 7 except that it has mounted thereon a "power control IC" 52. Power control IC 52 includes a pattern generator 54 that carries out the pattern generation function of IC tester 30 of FIG. 7 with respect to producing the control signals and data CNT1, CNT2 and CNT3 for controlling switches SW1 and SW2 and auxiliary power supply 38. Power control

IC 52 includes a conventional pattern generator 54 programmed before the start of a test by externally generated programming data provided via a conventional computer bus 56. Pattern generator 54 begins generating its output data pattern in response to a START signal from an IC tester 58 marking the start of a test and produces its output CNT1, CNT2, CNT3 data pattern in response to the same system clock (SYSCLK) that clocks operations of tester 58.

**[0050]** When the required capacitance C2 is sufficiently small, switches SW1 and SW2 and capacitors C2 may be implemented within power control IC 52 as shown in FIG. 9. IC 52 should be mounted on the probe card as near as possible to the DUT probes. Merging switches SW1 and SW2 and capacitors C2 and the pattern generation function of tester 30 into a single IC 52 reduces the cost and complexity of probe card 32 and reduces the required number of tester 30 output channels. However when necessary capacitors C2 can be implemented by discrete components external to power control IC 52.

#### Pulse Width Modulated Charge Flow

**[0051]** FIG. 10 illustrates an embodiment of the invention that is generally similar to the embodiment of FIG. 5. However in FIG. 10 switch SW1 is omitted from probe card 60 so that the VC output of auxiliary power supply 38 is directly connected to capacitors C2. Also the output voltage VC is fixed and not adjusted by IC tester 30 so that C2 charges to the same value prior to each CLOCK signal pulse. In this configuration IC tester 30 controls the amount of charge capacitors C2 deliver to DUTs 34 at the start of each CLOCK pulse by pulse width modulating switches SW2 via control signal CNT2. The amount of time tester 30 closes switches SW2 following the leading edge of a CLOCK signal pulse determines the amount of charge capacitors C2 deliver to DUTs 34. Alternatively, the shape of the I3 current flow illustrated in FIG. 6 can be more closely approximated when tester 30 rapidly increases and then decreases the duty cycle of the CNT2 signal as illustrated in FIG. 11.

#### Analog Modulated Charge Flow

**[0052]** FIG. 12 illustrates an embodiment of the invention that is generally similar to the embodiment of FIG. 10. However in FIG. 12 the transistor switches SW2 are replaced with transistors Q2 operated in their active regions when DUTs 34 are undergoing state changes and require additional current I3. In this

configuration, the CNT2 output of IC tester 30 is a data sequence applied as input to an analog-to-digital (A/D) converter 63 mounted on probe card 61. The data sequence CNT2 represents a predicted demand for charging current I3 during each CLOCK signal cycle. A/D converter 63 responds to the CNT2 data sequence by producing an analog signal CNT4 input to the bases of transistors Q2 that varies during each CLOCK signal cycle as illustrated in FIG. 13. Analog signal CNT4 controls the amount of current I3 each transistor Q2 allows to flow out of a capacitor C2 so that it substantially matches the predicted transient component of the current I1 demanded by DUT 34. A/D converter 63 may be implemented within IC tester 30 instead of being mounted on probe card 61.

#### Charge Prediction Using Reference DUT

**[0053]** FIG. 14 illustrate an embodiment of the invention wherein a reference DUT 60 similar to DUTs 34 is tested in a similar way except that tester 30 tests the reference DUT 60 slightly in advance of the other DUTs by advancing the CLOCK and other input signals it supplies to reference DUT 60. A main power supply 62 powers all DUTs 34 while an auxiliary power supply 64 powers reference DUT 60. A capacitor C4 mounted on probe card 66 near reference DUT 60 regulates the voltage VREF at its power input terminal 68 in a conventional manner so that it stays within its allowed operating range. A capacitor C5 links VREF to a set of amplifier's A1, and a capacitor C6 links the output of each amplifier A1 to the power input terminal 70 of each DUT 34.

**[0054]** Though well-regulated, the supply voltage VREF at the input terminal 68 of reference DUT 60 falls below its quiescent level by a small amount following the start of each CLOCK signal cycle due to the reference DUT's transient charging current demand. The amount of voltage decline in VREF is proportional to the amount of transient charging current drawn by reference DUT 60. Since reference DUT 60 is similar to DUTs 34 and is tested slightly in advance of DUTs 34, a decline in VREF predicts the amount of transient charging current each DUT 34 a short time later.

**[0055]** Amplifiers A1, acting through capacitors C5 and C6, amplify the AC component of VREF to produce output currents I3 that augment the current outputs I2 of main power supply 62 to provide the current input I1 to each DUT 34. The amount of time by which tester 30 advances the test of reference DUT 60 is set to

equal the delay between variations in reference voltage VREF and corresponding variations in currents I3. With the (negative) gain of each amplifier A1 appropriately adjusted by an externally generated signal (GAIN), currents I3 will substantially match the transient charging currents required by DUTs 34.

#### Charge Prediction In Non-Testing Environments

**[0056]** In addition to being useful for reducing power supply noise when testing integrated circuits, embodiments of the present invention can also be employed to reduce power supply noise in application in which an integrated circuit passes through a succession of states that can be predicted.

**[0057]** FIG. 15 illustrates an example embodiment of the invention in which an integrated circuit 80 passes through a predictable succession of states in response to edges of an externally generated CLOCK signal supplied as input thereto. IC 80 receives power from a main power supply 82. An auxiliary power supply 84 charges a capacitor C2 via a switch SW1 when switch SW1 is closed. Capacitor C2 supplies its charge as additional current input to IC 80 when a switch SW2 is closed. A "charge predictor" circuit 86 responds to the CLOCK signal by asserting a signal CNT1 to close switch SW1 and deasserting a control signal CNT2 to open switch SW2 during a portion of each CLOCK signal cycle in which IC 80 is not changing state. This allows auxiliary power supply 84 to charge capacitor C2 between state changes. Charge predictor circuit 86 asserts control signal CNT2 to close switch SW2 and deasserts control signal CNT1 to open switch SW1 during a portion of each CLOCK signal cycle in which IC 80 is changing state, thereby allowing capacitor C2 to deliver current to the power input of IC 80 to provide its transient current needs. Charge predictor 86 also provides control data CNT2 to auxiliary power supply 84 to adjust its output voltage VC so that it charges capacitor C2 to a level determined in accordance with an amount of current IC 80 is expected to draw during a next state change. Charge predictor 86 is suitably implemented by a conventional pattern generator or any other device capable of producing output data sequences CNT1, CNT2 and CNT3 that are appropriate for transient current requirements of IC 80 for its expected sequence of states. Switches SW1 and SW2 and/or capacitor C2 may be implemented either external to IC 80 as illustrated in FIG. 15 or may be implemented internal to IC 80.

## Charge Averaging

**[0058]** FIG. 16 illustrates a simple version of the invention suitable for use in applications wherein the amount of charging current an IC 80 is expected to draw at the start of each CLOCK signal cycle lies within a relatively limited, predictable range. As shown in FIG. 16, an inverter 90 inverts the CLOCK signal to provide the CNT1 control signal input to a switch SW1 coupling a main power supply to a capacitor C2. The CLOCK signal directly provides a CNT2 control signal input to a switch SW2 connecting capacitor C2 to a power input of IC 80 normally driven by a main power supply 82. As illustrated in FIG. 17, the CLOCK signal drives the CNT2 signal high to close switch SW2 during a first half of each CLOCK signal cycle and drives CNT1 high to close switch SW1 during a second half of each CLOCK signal cycle.

**[0059]** The output voltage VC of auxiliary power supply 84 is set to a constant value so that it charges capacitor C2 to the same level prior to the start of each CLOCK signal cycle. The level of VC is set to appropriately position the range over which power supply input voltage VB swings when IC 80 is drawing additional charging current at the start of each CLOCK signal cycle. For example when we want the quiescent value of VB to lie at the middle of its range, we can adjust VC so that capacitor C2 supplies an amount of charging current that is in the middle of the range of charging currents IC 80 is expected to draw. On the other hand, if we want to prevent VB from falling much below its quiescent value but are willing to allow VB to rise above its quiescent value, we can adjust VC so that capacitor C2 supplies the maximum amount of charging current IC 80 is expected to draw. While capacitor C2 may supply too little charging current during some CLOCK signal cycles and too much charging current during other CLOCK signal cycles, in many applications the system illustrated in FIG. 16 nonetheless can keep the swings in VB within acceptable limits when VC is suitably adjusted. Note that the systems of FIGS. 5, 9, 14 and 15 can be programmed to operate in a similar manner by setting control data CNT3 to the same value for every CLOCK signal cycle.

**[0060]** FIG. 18 illustrates another exemplary embodiment. As shown in FIG. 18, a power supply 36 provides power through a probe card 50 to a power input terminal 1806 on a semiconductor device under test (DUT) 34. A representation of

the inherent impedance through power line 1812 on the probe card 50 is illustrated in FIG. 18 as R1. As also shown in FIG. 18, an IC tester 58 provides clock and other signals through the probe card 50 to the DUT 34. A clock input terminal on exemplary DUT 34 is illustrated as terminal 1808. The IC tester 58 also receives signals through the probe card 50 from the DUT 34. One input/output (I/O) terminal 1810 is shown on DUT 34 in FIG. 18. However, DUT 34 may have additional I/O terminals 1810 or may have terminals dedicated solely to inputs and other solely to outputs or a combination of terminals dedicated to solely inputs or outputs and other terminals that function as both input and output terminals. It should be apparent that probe card 50 may make connections with one DUT as shown in FIG. 18 or a plurality of DUTs, for example, as shown in FIG. 14.

**[0061]** As shown in FIG. 18, a current sensing device 1804 (e.g., a current sense coupler or a current transformer) senses current through bypass capacitor C1. Amplifier 1802, which is preferably an inverting amplifier (e.g., the amplifier has a gain of minus one) provides current through capacitor C7 into transmission line 1812. An auxiliary power supply 38 provides power to amplifier 1802. Of course, power may be supplied to amplifier 1802 by other means, including from power supply 36, IC tester 58, a power supply located on the probe card 50, or a power supply located other than with the power supply 36, IC tester 58, or probe card 50.

**[0062]** In operation, power terminal 1806 typically draws little current, as described above (assuming DUT 34 includes primarily field effect transistors). Only under certain circumstances does power terminal 1806 draw a significant amount of current. As discussed above, the most common of these circumstances arises when at least one transistor in DUT 34 changes state, which typically occurs in correspondence with a rising or falling edge of the clock at clock terminal 1808.

**[0063]** While DUT 34 is not changing states, the small amount of current drawn at power terminal 1806 typically results in only a small and predominantly static direct current (DC) flow or no current flow through bypass capacitor C1. This results in little to no current sensed by current sensing device 1804, and consequently little to no current from inverting amplifier 1802.

**[0064]** While DUT 34 is changing states, however, power terminal 1806 temporarily draws a significant amount of current, as described above. This results in a temporary significant and changing flow of current through bypass capacitor



C1, as described above. That current is sensed by current sensing device 1804 and inverted and amplified by inverting amplifier 1802 and ultimately provided through isolation capacitor C7 into power line 1812. As described above, this extra current provided on power line 1812 by amplifier 1802 reduces variations in the voltage at power terminal 1806.

**[0065]** FIG. 19 illustrates a variation of the exemplary embodiment shown in FIG. 18. As shown, FIG. 19 is generally similar to FIG. 18 and also includes a current sensing element 1804 and an inverting amplifier 1802 configured to provide current to power line 1812 on probe card 50. However, in FIG. 19, the current sensing element 1804 senses current flow through the power line 1812 rather than through bypass capacitor C1.

**[0066]** FIG. 19 operates similarly to FIG. 18. That is, while DUT 34 is not changing states, the typically small, predominately static direct current (DC) drawn at power terminal 1806 and thus through power line 1804 results in little to no current sensed by current sensing device 1804 and, consequently, little to no current from inverting amplifier 1802.

**[0067]** While DUT 34 is changing states, however, the significant and changing amount of current drawn at power terminal 1806 and thus through power line 1804 is sensed by current sensing device 1804 and inverted and amplified by inverting amplifier 1802 and ultimately provided through isolation capacitor C7 into power line 1812. As described above, this extra current provided on power line 1812 by amplifier 1802 reduces variations in the voltage at power terminal 1806.

**[0068]** It should be apparent that the probe card illustrated in any of the above-described embodiments may be of just about any construction or design. For example, FIG. 20A illustrates a relatively simple probe card comprising a substrate 2002 with terminals 2004 for connecting to an IC tester (not shown in FIG. 20A) and probe elements 2008 for making electrical connections with a DUT (not shown in FIG. 20A). As shown, terminals 2004 are electrically connected to probe elements 2008 by interconnect elements 2006.

**[0069]** Substrate 2002 may be, for example, a single or multilayered printed circuit board or ceramic or other material. It should be apparent that the material composition of the substrate is not critical to the invention. Probes elements 2008 may be any type of probe capable of making electrical connections with a DUT including without limitation needle probes, COBRA style probes, bumps, studs,

posts, spring contacts, etc. Nonlimiting examples of suitable spring contacts are disclosed in U.S. Patent No. 5,476,211, U.S. Patent Application Serial No. 08/802,054, filed February 18, 1997, which corresponds to PCT publication WO 97/44676, U.S. Patent No. 6,268,015 B1, and U.S. Patent Application Serial No. 09/364,855, filed July 30, 1999, which corresponds to PCT publication WO 01/09952, which are incorporated by reference herein. Such spring contacts may be treated as described in U.S. Patent No. 6,150,186 or U.S. Patent Application Serial No. 10/027,476, filed December 21, 2001, which are also incorporated by reference herein. Alternatively, the "probes" may be pads or terminals for making contact with raised elements on the DUT, such as spring contacts formed on the DUT. Nonlimiting examples of interconnection paths 2006 include vias and/or a combination of vias and conductive traces located on a surface of substrate 2002 or within substrate 2002.

**[0070]** FIG. 20B illustrates another nonlimiting example of a probe card that may be used with the present invention. As shown, the exemplary probe card shown in FIG. 20B includes a substrate 2018, an interposer 2012, and a probe head 2032. Terminals 2022 make contact with an IC tester (not shown in FIG. 20B) and probe elements 2034, which may be similar to probe elements 2008 discussed above, make contact with a DUT (not shown in FIG. 20B). Interconnection paths 2020, resilient connection elements 2016, interconnection paths 2014, resilient connection elements 2010, and interconnection paths 2036 provide electrically conductive paths from terminals 2022 to probe elements 2034.

**[0071]** Substrate 2018, interposer 2012, and probe head 2032 may be made of materials similar to those described above with regard to 2002. Indeed, the material composition of the substrate 2018, the interposer 2012, and the probe head 2032 are not critical to the invention, and any composition may be used. Interconnection paths 2020, 2014, 2036 may be similar to interconnection paths 2006 as described above. Resilient connection elements 2016 and 2010 are preferably elongate, resilient elements. Nonlimiting examples of such elements are illustrated in U.S. Patent No. 5,476,211; U.S. Patent Application Serial No. 08/802,054, filed February 18, 1997, which corresponds to PCT publication WO 97/44676; U.S. Patent No. 6,268,015 B1; and U.S. Patent Application Serial No. 09/364,855, filed July 30, 1999, which corresponds to PCT publication WO 01/09952, all of which have been incorporated by reference herein. A more

detailed discussion of an exemplary probe card comprising a plurality of substrates, such as those shown in FIG. 20B, is found in U.S. Patent No. 5, 974,662, which is incorporated by reference herein. Many variations of the exemplary design shown in FIG. 20B are possible. As just one example, interconnection path 2014 may be replaced with a hole and one or more resilient elements 2016 and/or 2010 fixed within the hole and extending out of the hole to make contact with substrate 2018 and probe head 2032.

**[0072]** It should be apparent, however, that the construction or design of the probe card is not critical to the invention and any construction or design may be used. As shown in the embodiments described herein, circuitry for reducing variations in the voltage at a power terminal on a DUT is preferably disposed on the probe card. If a multisubstrate probe card is used, such as the exemplary probe shown in FIG. 20B, the circuitry may be located on any one of the substrates or may be distributed among two or more of the substrates. Thus, for example, the circuitry may be located on one of the probe head 2032, interposer 2012, or substrate 2018 illustrated in FIG. 20B, or the circuitry may be located on a combination of two or more of the probe head, the interposer, and/or the substrate. It should be apparent that the circuitry may be formed entirely of interconnected discrete circuit elements, may be formed entirely on an integrated circuit, or may consist in part of discrete circuit elements and in part of elements formed on an integrated circuit.

**[0073]** Thus has been shown and described a system for limiting power supply noise of an integrated circuit device when it is being tested. While the foregoing specification has described preferred embodiment(s) of the present invention, one skilled in the art may make many modifications to the preferred embodiment without departing from the invention in its broader aspects. While the invention is illustrated herein as reducing noise in a system employing only a single main power supply, it will be appreciated that the invention can be employed in environments in which more than one main power supply provide power to DUTs. Also while the apparatus is illustrated as operating in connection with DUTs having a single power input, it will be appreciated that the apparatus can be adapted to operate in connection with DUTs having multiple power inputs. For example referring to FIG. 7, if each DUT 34 had more than one power supply input terminal 41, an additional auxiliary power supply 38, an additional capacitor C2 and

additional switches SW1 and SW2 would be provided for each additional DUT power input terminal. Also, it should be noted that while the apparatus is described as providing additional charging current following a leading edge of a CLOCK signal pulse, it may be easily adapted to provide additional charging current following a trailing edge of the CLOCK signal pulse for use with DUTs that switch on trailing CLOCK signal edges. The appended claims therefore are intended to cover all such modifications as fall within the true scope and spirit of the invention.